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1 **Overpressure generating mechanisms in the Peciko Field, Lower Kutai Basin, Indonesia**

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5  
6 **Running title:** Overpressure generating mechanisms in the Peciko Field

7  
8 **ABSTRACT:** The Peciko Field contains gas in multiple stacked reservoirs within a Miocene  
9 deltaic sequence. In the deeper reservoirs, gas is trapped hydrodynamically by high lateral  
10 overpressure gradients. We have analysed overpressure and compaction in this field by using  
11 wireline log, pressure, temperature, and vitrinite reflectance data. The top of overpressure is  
12 located below 3 km burial depth, below the depth range for transformation of discrete  
13 smectite to mixed-layer illite/smectite. Density-sonic and density-resistivity crossplots for  
14 mudrocks show reversals within the transition zone into hard overpressure below 3.5 km  
15 depth. Vitrinite reflectance measurements indicate that the start of unloading coincides with  
16 the onset of gas generation. Moreover, mudrock density continues to increase with depth in  
17 the overpressured section to values above 2.6 g cm<sup>-3</sup>. We conclude that gas generation and  
18 chemical compaction are responsible for overpressure generation, contradicting previous  
19 interpretations that disequilibrium compaction is the principal mechanism for generating  
20 overpressure in the Lower Kutai Basin. The particular circumstances which make our radical  
21 interpretation plausible are that it is a warm basin with lateral reservoir drainage, so the  
22 overpressured mudrocks are probably overcompacted as a result of diagenesis.

23  
24 **KEYWORDS:** *Lower Kutai Basin, overpressure, unloading, gas generation, compaction*

26    **Introduction**

27    Overpressure in Cenozoic basins is commonly associated with the inability of fluid to escape  
28    rapidly enough to remain in hydrostatic equilibrium during ongoing burial. As a consequence,  
29    the sediments retain higher porosities than they would do if the pore pressure were  
30    hydrostatic. This process is referred to as disequilibrium compaction (Swarbrick *et al.* 2002).  
31    Disequilibrium compaction was recognized as a primary mechanism for generating  
32    overpressure in the US Gulf Coast region over 40 years ago (Pennebaker 1968; Reynolds  
33    1970). Since then, disequilibrium compaction has been diagnosed as the cause of overpressure  
34    in many sedimentary basins worldwide, including the Neogene prodelta mudrocks of the  
35    Baram Delta, Brunei (Tingay *et al.* 2009).

36

37        More recent work in overpressure analysis has shown the importance of other  
38    overpressure generating mechanisms apart from disequilibrium compaction, even in Neogene  
39    sequences. These overpressure generating mechanisms, such as gas generation, clay  
40    diagenesis, aquathermal pressuring and pressure transference, can be classified as unloading  
41    mechanisms (Bowers 1995). Some examples of basins where these mechanisms have been  
42    shown to be active are Haltenbanken and the Northern North Sea (Hermanrud *et al.* 1998;  
43    Teige *et al.* 1999, 2007), the Eugene Island area of the Gulf of Mexico (Bowers 2001), and  
44    the inner shelf sequence of the Baram Delta (Tingay *et al.* 2009).

45

46        The Peciko Field is located within Miocene strata in the Lower Kutai Basin,  
47    Kalimantan, Indonesia (Fig. 1). A transition zone into hard overpressure is encountered in the  
48    field at depths of 11,000–14,000 ft (3350–4250 m). The primary mechanism responsible for  
49    overpressure generation in this area has previously been interpreted to be disequilibrium  
50    compaction (Bois *et al.* 1994; Bates 1996; Burrus 1998).

51

52       The principal objective of the work reported here was to determine whether  
53 disequilibrium compaction really is the mechanism responsible for generating overpressure in  
54 the Peciko Field. A secondary aim was to find a method which can be used during drilling  
55 mudrock sections to estimate overpressure for wider application in the basin. By analysing  
56 wireline log data in the mud-rich intervals, we show that overpressure is generated by  
57 unloading mechanisms, probably including both gas generation and clay mineral diagenesis,  
58 and not disequilibrium compaction. Our interpretation is radically different from that of  
59 previous workers, who have all concluded that the principal mechanism for generating  
60 overpressure was disequilibrium compaction.

61

62       In the following sections, we give background on the geology of the basin,  
63 overpressure distribution, and wireline log responses to overpressure before presenting our  
64 analysis of log, pressure, temperature, and vitrinite reflectance data. We then discuss the  
65 implications for overpressure generation mechanisms and, in reaching our conclusions,  
66 comment on the particular circumstances in the Lower Kutai Basin which make it a rewarding  
67 basin to study for understanding overpressure generation and chemical compaction in mud-  
68 rich sedimentary successions.

69

## 70 **Geological background and overpressure distribution**

71 Tectonically, the Lower Kutai Basin has experienced several episodes of rift, sag, and  
72 inversion resulting from interaction between the Eurasia plate to the north, the Pacific Plate to  
73 the east, and the Australian Plate to the south (Moss & Chambers 1999). The main inversion  
74 episodes have occurred from the Middle Miocene to the present, and have been responsible  
75 for the development of anticlinal structures (Chambers *et al.* 2004). The major structural

76 feature is the Samarinda Anticlinorium, consisting of a series of anticlines and synclines with  
77 axes oriented approximately north–south. This anticlinorium is highly folded and faulted on  
78 the onshore area, whereas dips are gentle in the shallow water and deep offshore areas. The  
79 main north–south anticlinal folds are the Onshore Axis, Internal Axis, Median Axis, External  
80 Axis, and Offshore Axis (Fig. 1). The Peciko Field is located on the Median Axis.

81

82         According to Allen & Chambers (1998), the thickness of the Neogene section in the  
83 basin, which comprises deltaic sediment sourced by the Mahakam River in eastern  
84 Kalimantan, may reach about 14 km in the depocentre. The Mahakam Delta is a fluvial-tidal  
85 mud-dominated delta that has been prograding from the Early Miocene to the present day.  
86 Stratigraphically, the productive interval in the Middle–Upper Miocene succession is the  
87 Tunu Main Zone, and the hydrocarbons present are mainly gas. The Tunu Main Zone is sub-  
88 divided into six intermediate stratigraphic units, of which only the uppermost five are present  
89 in the Peciko Field. They have an average thickness of 300–400 m, based on the presence of  
90 third-order maximum flooding surfaces. The intermediate stratigraphic units are further sub-  
91 divided into several smaller stratigraphic units, based on the presence of local flooding  
92 surfaces. The reservoirs in this field are dominantly distributary mouth bars (Samson *et al.*,  
93 2005). The dimensions of individual mouth bars are 1–3 m thick and 1500–4000 m wide, and  
94 stacked mouth bars attain thicknesses of 10–30 m (Fig. 2a). Figure 2b is a schematic cross-  
95 section of the field which illustrates the stacked nature of the gas reservoirs and the tilted gas-  
96 water contacts in the deeper overpressured accumulations.

97

98         The burial history of the Tunu Main Zone in this field (Fig. 3) shows that the  
99 sedimentation rate during the last 8 My has been fairly constant at around 300 m My<sup>-1</sup>. This  
100 ongoing deposition of fine-grained sediment has previously been interpreted as being

101 responsible for the generation of overpressure by disequilibrium compaction in this area (Bois  
102 *et al.* 1994; Bates 1996; Burrus 1998).

103

104         The inversion episodes have caused almost all of the Neogene sedimentary layers to  
105 crop out in the onshore and coastal areas. Consequently, overpressure can bleed off laterally  
106 on the basin scale, depending on the degree of reservoir connectivity. This process is known  
107 as lateral reservoir drainage (O'Connor & Swarbrick 2008). The occurrence of lateral  
108 reservoir drainage in the Peciko Field was identified by Grosjean *et al.* (1994) and Lambert *et*  
109 *al.* (2003). The lateral overpressure gradients are sufficiently large to create hydrodynamic  
110 traps for gas. For example, in stratigraphic unit 3 the lateral overpressure gradient reaches 150  
111 psi km<sup>-1</sup> (Fig. 4a). Given a gas density of 0.2 g cm<sup>-3</sup>, the gas-water contact has a tilt of up to  
112 7°. There is ample field evidence of tilted accumulations of gas in the deeper reservoir  
113 intervals of the Peciko Field. In these reservoirs, the gas accumulations are displaced down-  
114 dip on to the northern flank of the structure, as shown schematically in Fig. 2b, and the gas  
115 column in crestal wells is either very thin or absent (Fig. 4b). A south–north cross-section  
116 (Fig. 5) shows that both top of overpressure and the top of the pressure transition zone deepen  
117 to the north, where the strata are more sand-rich.

118

119         Information about source rocks in the Lower Kutai Basin generally, and in the Peciko  
120 Field specifically, has been provided by Oudin & Picard (1982), Schoell *et al.* (1985), Burrus  
121 *et al.* (1992), Paterson *et al.* (1997), Duval *et al.* (1998), and Lambert *et al.* (2003). The main  
122 source rocks in the area are organic-rich mudrocks, coal beds, and even sandy facies  
123 deposited in fluvial, deltaic top, tidal plain, and delta front settings. They are mostly classified  
124 as Type III source rocks. Although the organic-rich mudrocks are gas prone, Lambert *et al.*  
125 (2003) reported that the oil-generative potential of the Type III organic matter is unusually

126 high. The contribution to hydrocarbon generation from marine mudrocks, located in the  
127 deepwater Makassar Straits and in the deeper part of fields surrounding Mahakam Delta, is  
128 thought to be negligible because their organic content is low. Interestingly, isotopic analysis  
129 performed by Lambert *et al.* (2003) showed that the threshold for both gas and oil maturation  
130 corresponds to a vitrinite reflectance of 0.6%.

131

### 132 **Wireline log responses to overpressure**

133 There are several candidate mechanisms for generating overpressure in the Lower Kutai  
134 Basin, including disequilibrium compaction, clay diagenesis, gas generation, and lateral  
135 pressure transfer. Wireline log analysis can help to distinguish between these mechanisms  
136 (e.g. Bowers 2001; Katahara 2006).

137

138       When a mud-rich sedimentary succession cannot dewater rapidly enough for the pore  
139 pressure to remain hydrostatic during burial, its porosity is greater than that it would be if the  
140 pore pressure were hydrostatic, and the overpressure is said to be caused by disequilibrium  
141 compaction. Where overpressure has been generated by disequilibrium compaction in a  
142 uniform mudrock succession, with virtually no loss of pore fluid, the porosity remains  
143 constant and the pore pressure-depth profile becomes parallel to the vertical stress-depth  
144 profile.

145

146       Where overpressure has been generated by an unloading mechanism such as clay  
147 diagenesis, gas generation or lateral transfer, the pore pressure can increase more rapidly with  
148 depth than the vertical stress (Fig. 6). In such circumstances, the density usually continues to  
149 increase with depth through the overpressured mudrocks, while the sonic log trend reverses,  
150 moving towards higher sonic travel time with increasing depth. The resistivity log trend also

151 reverses, moving towards lower resistivity with increasing depth. These responses can be  
152 explained by the concept of storage pores and connecting pores (Bowers & Katsube 2002).  
153 When pore pressure in a mudrock increases due to fluid expansion, the unloading response is  
154 essentially elastic and results in only a very small increase in porosity. Because the density  
155 log measures the bulk porosity of the mudrock, it is barely affected by the fluid expansion.  
156 The increase in porosity that does occur during fluid expansion is predominately due to the  
157 opening of flat connecting pores, because they are more compliant than the storage pores. The  
158 sonic and resistivity log responses are sensitive to the opening of connecting pores because  
159 their opening reduces the bulk modulus and rigidity and increases the conductivity.

160

#### 161 **Data analysis**

162 The Peciko Field was developed using the concept of hydrodynamic trapping (Grosjean *et al.*  
163 1994; Lambert *et al.* 2003), and a campaign of reservoir pressure measurements for  
164 hydrodynamic analysis purposes has resulted in an excellent pressure database. On average,  
165 there are around 70 RFT points in each well. These pressure data are very useful for  
166 overpressure analysis because they can be used both to determine overpressure distribution  
167 and to calibrate methods of pore pressure estimation.

168

169 We have analysed data from the discovery well, PEC-1, and 16 appraisal wells in the  
170 Peciko Field, most of which have terminated at the pressure transition zone into hard  
171 overpressure. Here, we present data from three wells, PEC-1, NWP-9, and NWP-16 (Fig. 2a),  
172 to illustrate our findings. PEC-1 was chosen as a typical example of a well on the crest of the  
173 structure and because source rock maturation data are available from it, although it does  
174 contain a relatively small number of RFT points and no density log was run in this early well.  
175 NWP-9 was chosen because it encounters the highest overpressure value in the Peciko Field



176 and shows a clear unloading response on density-sonic and density-resistivity crossplots.  
177 NWP-16 is located downflank in the northern part of the field where the top of overpressure is  
178 deeper and the geothermal gradient is slightly lower (Fig. 3). It is the deepest well in the field  
179 and was chosen to make a comparison of the wireline log responses with those from well  
180 NWP-9.

181

182 Prior to analysing the wireline response to overpressure, it is necessary to discriminate  
183 mud-rich intervals from more silty and sandy intervals from the given set of wireline logs.  
184 Discrimination was done by cross-plotting density against the difference between neutron  
185 porosity and the porosity estimated from the density logs (Fig. 7), as done by Katahara  
186 (2006). To infer porosity from the density log, a matrix density of  $2.75 \text{ g cm}^{-3}$  and a fluid  
187 density of  $1.05 \text{ g cm}^{-3}$  were arbitrarily assumed. An arbitrary threshold value of 0.18 was  
188 chosen (i.e.,  $\text{NPHI} - \text{DPHI} > 0.18$ ) to ensure that our pressure analysis was consistently  
189 performed in the mud-rich intervals, although tests showed that estimated pore pressures in  
190 the mudrocks had low sensitivity to the choice of threshold value.

191

192 The pressure-depth plot for well PEC-1 (Fig. 8a) is typical of wells in this field, except  
193 that the top of overpressure is located at slightly greater depths further north (Fig. 3). The  
194 overpressure initially increases slowly with depth below the top of overpressure at ~9500 ft  
195 (~2900 m) and then more rapidly through a transition zone into hard overpressure. The top of  
196 the transition zone is at ~11,300 ft (~3450 m). The top of transition zone is picked at the depth  
197 where vertical effective stress starts to decrease as depth increases.

198

199 According to Lambert *et al.* (2003), the maturity threshold for gas generation  
200 corresponds to a vitrinite reflectance value of 0.6%. Well PEC-1 is the only well in the

201 Peciko Field from which vitrinite reflectance data are available (Fig. 8b). There is a  
202 correlation between the top of the transition zone into hard overpressure and the vitrinite  
203 reflectance value of 0.6%. Four data points in the interval 10,000–12,000 ft (3050–3650 m)  
204 have vitrinite reflectance values below the general trend. There is no other available  
205 information to indicate whether they are reliable, but there is a possibility that these values  
206 were obtained from fragments due to caving, and not cuttings from the drill bit.

207

208         The pressure-depth plot for well NWP-9 (Fig. 9) indicates that the top of overpressure  
209 is at a depth of ~11,000 ft (~3350 m), although there is a good RFT measurement showing  
210 ~300 psi (~2 MPa) of overpressure in an isolated sand body at ~10,000 ft (~3050 m) depth.  
211 The top of the transition into hard overpressure is around 12,000 ft (3650 m) depth, where  
212 reversals can be seen in the trends of both the sonic and resistivity logs through the mudrocks.  
213 The density log, by contrast, shows no obvious reversal, but it shows consistently high values  
214 of density, around  $2.6 \text{ g cm}^{-3}$ , in the depth interval 11,000–13,000 ft (3350–3950 m).

215

216         The pressure-depth plot for well NWP-16 (Fig. 10) appears to converge slightly  
217 towards the lithostatic gradient with increasing depth, but it is not clear whether the well has  
218 entered the expected transition zone into hard overpressure. The wireline logs appear to  
219 display asymptotic trends towards the bottom of the well, without any clear indication of  
220 reversals, although it is possible that the trends of both sonic and resistivity logs are on the  
221 point of reversing at the bottom of the well.

222

223         Crossplots of density against sonic and resistivity log values for mudrocks in well  
224 NWP-9 are shown in Fig. 11, with data points colour-coded at intervals of 1000 ft (305 m).  
225 The smectitic and illitic compaction trends, introduced by Dutta (2002) and adopted by

226 Katahara (2006), are shown on the density-sonic crossplot for reference. The smectitic  
227 compaction trend is followed by mudrocks with a high proportion of discrete smectite. The  
228 illitic compaction trend is followed by mudrocks in which all the discrete smectite has been  
229 transformed into mixed-layer illite/smectite. Both crossplots show clear unloading responses  
230 starting at a depth of ~12,000 ft (~3650 m). The data points coloured red in the deepest  
231 interval show changes in trend, with increased sonic transit time and decreased resistivity but  
232 no decrease in density. These observations provide clear evidence that the generating  
233 mechanism for hard overpressure is an unloading process. Data points in the depth range  
234 5000–12,000 ft (1500–3650 m) on the density-sonic crossplot fall on, or close to, the illitic  
235 compaction trend. The average geothermal gradient is around  $0.0094\text{ }^{\circ}\text{C ft}^{-1}$  ( $0.031\text{ }^{\circ}\text{C m}^{-1}$ )  
236 with a surface temperature of  $30^{\circ}\text{C}$ , giving an estimated temperature of nearly  $80^{\circ}\text{C}$  at 5000 ft  
237 (1500 m) depth, sufficient for discrete smectite to have disappeared (Hower *et al.* 1976; Boles  
238 & Franks 1979).

239

240 Clauer *et al.* (1999) investigated clay mineralogy in the Tunu Field, which is located  
241 on the Median Axis north of Peciko (Fig. 1) so the clay mineralogy in the two fields may be  
242 expected to be similar. At sampling depths below 7700 ft (2350 m), they found that the clay  
243 fraction consists of mixed-layer illite/smectite, kaolinite/dickite, detrital illite and chlorite.  
244 This clay mineral composition is consistent with the illitic compaction trend observed below  
245 ~5000 ft (~1500 m) (Fig. 11). The fact that the density-sonic crossplot follows an illitic  
246 compaction trend over the hydrostatically pressured depth interval of 5000–11,000 ft (1500–  
247 3350 m) indicates that excess water which may have been released by the transformation of  
248 discrete smectite to mixed-layer illite/smectite has dissipated and does not contribute to  
249 present-day overpressures. However, clay diagenetic reactions that continue to be active at  
250 higher temperatures, including ongoing illitization of mixed-layer illite/smectite and the

251 conversion of kaolinite to illite (Bjørlykke 1998), and also quartz dissolution and precipitation  
252 (Bjørkum 1995), probably do contribute to present-day overpressures.

253

254 Composite density plots for mudrocks in all 16 NWP wells (Fig. 4a) are shown in Fig.  
255 12, without and with the data points from the overpressured intervals in each well. The  
256 density continues to increase smoothly below the top of overpressure, even though the vertical  
257 effective stress reaches its maximum value at the top of overpressure in each well. Thus,  
258 compaction appears to continue with increasing depth, independent of the vertical effective  
259 stress. This plot constitutes strong evidence for ongoing chemical compaction below the top  
260 of overpressure, and for discounting disequilibrium compaction as a mechanism that  
261 contributes to the generation of overpressure in this field. Given the high average density, in  
262 excess of  $2.6 \text{ g cm}^{-3}$  below 12,000 ft in all wells (Fig. 12), our preferred interpretation is that  
263 the mudrocks in the overpressured intervals have become overcompacted by diagenetic  
264 processes, i.e. overcompacted in a mechanical sense due to the chemical compaction  
265 processes.

266

### 267 **Implications for overpressure generation**

268 Pressure-depth plots show that the top of overpressure is at depths of 9500–12,000 ft (2900–  
269 3650 m), corresponding to estimated temperatures of 120–140°C, and that there is a transition  
270 zone into hard overpressure at depths of 11,500–14,000 ft (3500–4250 m), corresponding to  
271 estimated temperatures of 140–160°C. These depths to the top of overpressure are relatively  
272 large in comparison to other Neogene basins worldwide, as summarized by Swarbrick *et al.*  
273 (2002). For example, in the Malay Basin where the sedimentation rate is around  $800 \text{ ft My}^{-1}$   
274 ( $240 \text{ m My}^{-1}$ ), about 20% less than the sedimentation rate over the last 8 My in the Lower  
275 Kutai Basin, the top of overpressure is around 3200 ft (975 m) depth. Presumably, the top of

276 overpressure in the Lower Kutai Basin is so deep because of lateral reservoir drainage  
277 (Grosjean *et al.* 1994; Lambert *et al.* 2003). Inversion started in Middle Miocene times and  
278 has continued to the present day with uplift centred on the onshore area (Chambers *et al.*  
279 2004). Unpublished net-to-gross (NTG) maps for the Median Axis region of the Lower Kutai  
280 Basin show a progressive upward increase in NTG at the Peciko Field from stratigraphic unit  
281 5 up to stratigraphic unit 3 (Figs 2b and 5), which is consistent with effective lateral drainage  
282 above the overpressured zone.

283

284         Within the transition zone into hard overpressure in well NWP-9, both density-sonic  
285 and density-resistivity crossplots show clear unloading responses (Figs 9 and 11). Clay  
286 diagenesis may contribute to the present-day overpressure in the Peciko Field. In the  
287 hydrostatically pressured succession, data on the density-sonic crossplots lie on the illite-rich  
288 compaction trend below ~5000 ft (~1500 m), and remain on this trend in the zone of low  
289 overpressure (Fig. 10). Although discrete smectite is likely to have disappeared by 5000 ft  
290 (1500 m) burial depth, where the temperature approaches 80°C, illitization of mixed-layer  
291 illite/smectite is ongoing at greater depths to much higher temperatures (Hower *et al.* 1976;  
292 Boles & Franks 1979). Kaolinite transforms to illite at temperatures ~130–140°C in basin  
293 settings (Bjørlykke 1998) and can contribute to overpressure both through the release of free  
294 water by the reaction and by transferring load from the grains to the pore fluid as mineral  
295 grains are dissolved (Bjørlykke & Hoeg 1997). This temperature range roughly corresponds  
296 to that estimated at the depth of the transition zone into high overpressure. Furthermore, the  
297 dissolution of kaolinite and precipitation of illite may reduce porosity and permeability at this  
298 depth, and thereby help to maintain high overpressure in the deeper strata.

299

300 Gas generation seems likely to be another unloading process responsible for the hard  
301 overpressure, generated both directly from kerogen and from oil cracking to gas. According to  
302 Lambert *et al.* (2003), gas generation starts at a vitrinite reflectance of 0.6%. We have one set  
303 of vitrinite reflectance data in the Peciko Field, i.e. in PEC-1 where there is a correlation  
304 between high overpressure and vitrinite reflectance values above 0.6% (Fig. 7). Oudin &  
305 Picard (1982) found that there is a good correlation between the top of hard overpressure and  
306 the increase in vitrinite reflectance in the Handil Field (Fig. 13), and Bates (1996) found a  
307 similar correlation in the Nilam Field (Fig. 14). However, they did not draw any conclusions  
308 about overpressure generation mechanisms from the vitrinite reflectance data. We note that  
309 the data in each of those two wells show a strong correlation between the depth of transition  
310 into hard overpressure and the onset of gas generation, assuming that the threshold for gas  
311 generation corresponds to a vitrinite reflectance of 0.6%.

312

313 To the south and east of the Peciko Field, the sands within the Tunu Main Zone peter  
314 out as the depositional environment changes from the shelf break setting to deep marine.  
315 Since the organic carbon content of the deep marine sediment is low and its potential for  
316 hydrocarbon generation is negligible, there is unlikely to be significant lateral transfer of  
317 overpressure generated by gas generation in the synclinal area to the southeast, but there may  
318 be lateral transfer of overpressure generated by diagenetic reactions.

319

320 In all wells with density logs, NWP-1 to NWP-16, the logged density values continue  
321 gradually to increase downwards through the zone of low overpressure (Fig. 12), which is  
322 consistent with ongoing chemical compaction. The top of overpressure is located deep within  
323 the chemical compaction zone, where the effective stress appears to have no influence on  
324 compaction and the mudrocks are likely to be stiffened by chemical compaction so that they

325 are overconsolidated (Bjørlykke & Hoeg 1997; Bjørlykke 1998, 1999). Consequently, we  
326 attribute the origin of the low overpressures, above the transition zone into hard overpressure,  
327 to passive transmission of pore fluid from the highly overpressured zone below.

328

## 329 **Conclusions**

330 Hard overpressure in the Peciko Field is generated by unloading mechanisms. The top of  
331 overpressure is much deeper than the depth range where transformation of discrete smectite to  
332 mixed-layer smectite/illite occurs, so the disappearance of smectite does not contribute to the  
333 observed overpressure. The causes of the hard overpressure in the Peciko Field are likely to  
334 be gas generation, illitization of mixed-layer illite/smectite, conversion of kaolinite to illite,  
335 and dissolution and precipitation of quartz. We suggest that expulsion of fluid resulting from  
336 gas generation and diagenesis in the zone of high overpressure maintains the hydrodynamic  
337 flow through the reservoir layers containing gas accumulations.

338

339       Compaction continues below the top of overpressure, independent of vertical effective  
340 stress, in all 16 wells where density logs have been run. This observation is clear evidence of  
341 ongoing chemical compaction. The origin of the low overpressure above the transition zone  
342 into high overpressure is probably due to vertical transfer from below. The transition zone  
343 into hard overpressure can be recognized from sonic and resistivity log reversals, whether by  
344 direct inspection of the logs or by crossplotting their responses against the density log.

345

346       The high mudrock densities, greater than  $2.6 \text{ g cm}^{-3}$ , at the top of overpressure indicate  
347 that the mudrocks are overcompacted. Therefore, our preferred interpretation is that  
348 disequilibrium compaction does not contribute to the overpressure. This conclusion is  
349 radically new because all other studies of overpressured Neogene basins have suggested that

350 disequilibrium compaction has contributed to the overpressure, either directly or indirectly by  
351 pressure transference. The particular circumstances in the Lower Kutai Basin which make our  
352 interpretation plausible are that it is a warm basin with lateral reservoir drainage.  
353 Consequently, the top of overpressure is unusually deep for a mud-rich sequence that has  
354 undergone rapid burial over the last 10 My.

355

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361

### 362 **References**

363

364 Allen, G. P. & Chambers, J. L. C. 1998. *Sedimentation in the Modern and Miocene Mahakam*  
365 *Delta*. Field Trip Guide Book, Indonesian Petroleum Association, Jakarta.

366

367 Bates, J. A. 1996. Overpressuring in the Kutai Basin: distribution, origins, and implications  
368 for the petroleum system. *In: Indonesian Petroleum Association, Proceedings 25th Annual*  
369 *Convention*, 93-115.

370

371 Bjørkum, P. A. 1995. How important is pressure in causing dissolution of quartz in  
372 sandstones? *Journal of sedimentary Research*, **66**, 147-154.

373



374 Bjørlykke, K. 1998. Clay mineral diagenesis in sedimentary basins: a key to the prediction of  
 375 rock properties: examples from the North Sea Basin. *Clay Minerals*, **33**, 15–34.

376

377 Bjørlykke, K. 1999. Principal aspects of compaction and fluid flow in mudstones. *In*: Aplin,  
 378 A.C., Fleet, A.J. & Macquaker, J.H.S. (eds) *Muds and Mudstones: Physical and Fluid-Flow*  
 379 *Properties*. Geological Society, London, Special Publications, **158**, 73-78.

380

381 Bjørlykke, K. & Høeg, K. 1997. Effects of burial diagenesis on stresses, compaction and fluid  
 382 flow in sedimentary basins. *Marine and Petroleum Geology*, **14**, 267-276.

383

384 Bois, M., Grosjean, Y. & de Pazzis, L. 1994. Shale compaction and abnormal pressure  
 385 evaluation application to the offshore Mahakam. *In*: *Indonesian Petroleum Association,*  
 386 *Proceedings 23rd Annual Convention*, 245-259.

387

388 Boles, J. R. & Franks, S. G. 1979. Clay diagenesis in Wilcox sandstones of southwest Texas:  
 389 implications of smectite diagenesis on sandstone cementation. *Journal of Sedimentary*  
 390 *Petrology*, **49**, 55-70.

391

392 Bowers, G. L. 1995. Pore pressure estimation from velocity data: accounting for overpressure  
 393 other than undercompaction. *SPE Drilling & Completion*, **10**(2), 89-95.

394

395 Bowers, G. L. 2001. Determining an appropriate pore-pressure estimation strategy. *Offshore*  
 396 *Technology Conference*, paper OTC 13042.

397

398 Bowers, G. L. & Katsube, T. J. 2002. The role of shale pore structure on the sensitivity of  
399 wire-line logs to overpressure. *In: Huffman, A.R. & Bowers, G.L. (eds), Pressure Regimes in*  
400 *Sedimentary Basins and their Prediction*. AAPG, Tulsa, Memoir **76**, 43-60.

401

402 Burrus, J. 1998. Overpressure models for clastic rocks, their relation to hydrocarbon  
403 expulsion: a critical reevaluation. *In: Law, B.E., Ulmishek, G.F. & Slavin, V.I. (eds)*  
404 *Abnormal Pressures in Hydrocarbon Environments*. AAPG, Tulsa, Memoir **70**, 35-63.

405

406 Burrus, J., Brosse, E., Choppin de Janvry, G., Grosjean, Y. & Oudin, J. L. 1992. Basin  
407 modelling in the Mahakam Delta based on integrated 2D model Temispack. *In: Indonesian*  
408 *Petroleum Association, Proceedings 21st Annual Convention*, 23-43.

409

410 Chambers, J. L. C., Carter, I., Cloke, R., Craig, J., Moss, S. J. & Paterson, D. W. 2004. Thin-  
411 skinned and thick-skinned inversion-related thrusting – a structural model for the Kutai Basin,  
412 Kalimantan, Indonesia. *In: McClay, K.R. (ed.) Thrust Tectonics and Hydrocarbon Systems*.  
413 AAPG, Tulsa, Memoir **82**, 614-634.

414

415 Clauer, N., Rinckenbach, T., Weber, F., Sommer, F., Chaudhuri, S. & O’Neil, J. R. 1999.  
416 Diagenetic evolution of clay minerals in oil-bearing Neogene sandstones and associated  
417 shales, Mahakam Delta Basin, Indonesia. *AAPG Bulletin*, **83**, 62-87.

418

419 Dutta, N. C. 2002. Deepwater geohazard prediction using prestack inversion of large offset P-  
420 wave data and rock model. *The Leading Edge*, **21**, 193-198.

421

422 Duval, B. C., Cassaigneau, C., Choppin de Janvry, G., Loiret, B., Leo, M., Alibi & Grosjean,  
 423 Y. 1998. Impact of the petroleum system approach to exploration and appraisal efficiency in  
 424 the Mahakam Delta. *In: Indonesian Petroleum Association, Proceedings 26th Annual*  
 425 *Convention*, 277-290.  
 426  
 427 Grosjean, Y., Choppin de Janvry, G. & Duval, B. C. 1994. Discovery of a giant in a mature  
 428 deltaic province: Peciko, Indonesia. Presented at the 14<sup>th</sup> World Petroleum Congress, May–  
 429 June 1994, Stavanger, Norway.  
 430  
 431 Hermanrud, C., Wensaas, L., Teige, G. M. G., Vik, E., Nordgård Bolås, H. M. & Hansen, S.  
 432 1998. Shale porosities from well logs on Haltenbanken (Offshore Mid-Norway) show no  
 433 influence of overpressuring. *In: Law, B.E., Ulmishek, G.F. & Slavin, V.I. (eds.) Abnormal*  
 434 *Pressures in Hydrocarbon Environments*. AAPG, Tulsa, Memoir **70**, 65-87.  
 435  
 436 Hower, J., Eslinger, E. V., Hower, M. E. & Perry, E. A. 1976. Mechanism of burial and  
 437 metamorphism of argillaceous sediment : 1. Mineralogical and chemical evidence. *Geological*  
 438 *Society of America Bulletin*, **87**, 725-737.  
 439  
 440 Katahara, K. 2006. Overpressure and shale properties: stress unloading or smectite-illite  
 441 transformation? 76<sup>th</sup> *SEG Annual Meeting*, Expanded Abstracts, 1520-1524.  
 442  
 443 Lambert, B., Duval, B. C., Grosjean, Y., Umar, I. M. & Zaugg, P. 2003. The Peciko case  
 444 history: impact of an evolving geological model on the dramatic increase of gas reserves in  
 445 the Mahakam Delta. *In: Halbouty, M.T. (ed.) Giant Oil and Gas Fields of the Decade 1990–*  
 446 *1999*. AAPG, Tulsa, Memoir **78**, 297-320.

447

448 Moss, S. J. & Chambers, J. L. C. 1999. Depositional modelling and facies architecture of rift  
449 and inversion episodes in the Kutai Basin, Kalimantan, Indonesia. *In: Indonesian Petroleum*  
450 *Association, Proceedings 27th Annual Convention*, 467-486.

451

452 O'Connor, S. A. & Swarbrick, R. E. 2008. Pressure regression, fluid drainage and a  
453 hydrodynamically controlled fluid contact in the North Sea, Lower Cretaceous, Britannia  
454 Sandstone Formation. *Petroleum Geoscience*, **14**, 115-126.

455

456 Oudin, J. L. & Picard, P. F. 1982. Genesis of hydrocarbons in Mahakam Delta and the  
457 relationship between their distribution and the overpressured zone. *In: Indonesian Petroleum*  
458 *Association, Proceedings 11th Annual Convention*, 181-202.

459

460 Paterson, D. W., Bachtiar, A., Bates, J. A., Moon, J. A. & Surdam, R. C. 1997. Petroleum  
461 system of the Kutei Basin, Kalimantan, Indonesia. *In: Indonesian Petroleum Association,*  
462 *Proceedings Petroleum Systems of SE Asia and Australasia Conference*, 709-726.

463

464 Pennebaker, E. S. 1968. Seismic data indicate depth and magnitude of abnormal pressure.  
465 *World Oil*, **166**, 73-82.

466

467 Reynolds, E. B. 1970. Predicting overpressure zones with seismic data. *World Oil*, **171**, 78-  
468 82.

469

470 Samson, P., Dewi-Rochette, T. & Lescoeur, M. 2005. Peciko geological modeling: optimizing  
 471 fluid distribution and model resolution of a giant gas field in a shale-dominated deltaic  
 472 environment. Asia Pacific Oil & Gas Conference, SPE paper 93253.  
 473

474 Schoell, M. B., Durand, B. & Oudin, J. L. 1985. Migration of oil and gas in the Mahakam  
 475 Delta: evidence and quantitative estimate from isotope and biomarker studies. *In: Indonesian*  
 476 *Petroleum Association, Proceedings 14th Annual Convention*, 49-56.  
 477

478 Swarbrick, R. E., Osborne, M. J. & Yardley, G. S. 2002. Comparison of overpressure  
 479 magnitude resulting from the main generating mechanisms. *In: Huffman, A.R. & Bowers,*  
 480 *G.L. (eds) Pressure Regimes in Sedimentary Basins and their Prediction*. AAPG, Tulsa,  
 481 *Memoir 76*, 1-12.  
 482

483 Teige, G. M. G., Hermanrud, C., Wensaas, L. & Nordgård Bolås, H. M. 1999. The lack of  
 484 relationship between overpressure and porosity in North Sea and Haltenbanken shales.  
 485 *Marine and Petroleum Geology*, **16**, 321-335.  
 486

487 Teige, G. M. G., Hermanrud, C., Wensaas, L. & Nordgård Bolås, H. M. 2007. Geological  
 488 constraints of pore pressure detection in shales from seismic data. *Basin Research*, **19**, 33-50.  
 489

490 Tingay, M. R. P., Hillis, R. R., Swarbrick, R. E., Morley, C. K. & Damit, A. R. 2009. Origin  
 491 of overpressure and pore-pressure prediction in the Baram province, Brunei. *AAPG Bulletin*,  
 492 **83**, 51-74.  
 493  
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495 **Figure captions**

496

497 Figure 1. Major structural features in the Lower Kutai Basin. The main north–south anticlines  
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499

500 Figure 2. Schematic sections through the Peciko Field at different vertical scales: (a) stacked  
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502 2005); and (b) gas accumulations (red) with tilted GWCs in the Tunu Main Zone. SU1–SU5  
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507 *al.* 2003).

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511 well, PEC-1, and the 16 NWP appraisal wells. Overpressure contours are at intervals of 50  
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513 Pore fluid distribution in the same stratigraphic unit showing that the gas accumulation is  
514 located on the north flank of the structure. Red line: limit of the gas accumulation in this  
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517 thickness in each well. Structural contour interval is 82 ft (25 m).

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520 4a showing the general trend of overpressure with depth.

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522 Figure 6. Pressure-depth plot (right) with sonic and density log responses expected for a  
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524 of overpressure, the reversal in the trend of sonic transit time does not indicate abnormally  
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527 Figure 7. Crossplot of density against the difference between neutron and density porosities  
528 estimated from wireline logs in well NWP-9.  $NPHI - DHPI = 0.18$  was arbitrarily chosen as  
529 the mudrock cut-off.

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536 Figure 9. Pressure-depth plot for well NWP-9 with density, sonic, and resistivity log data for  
537 the mudrocks.

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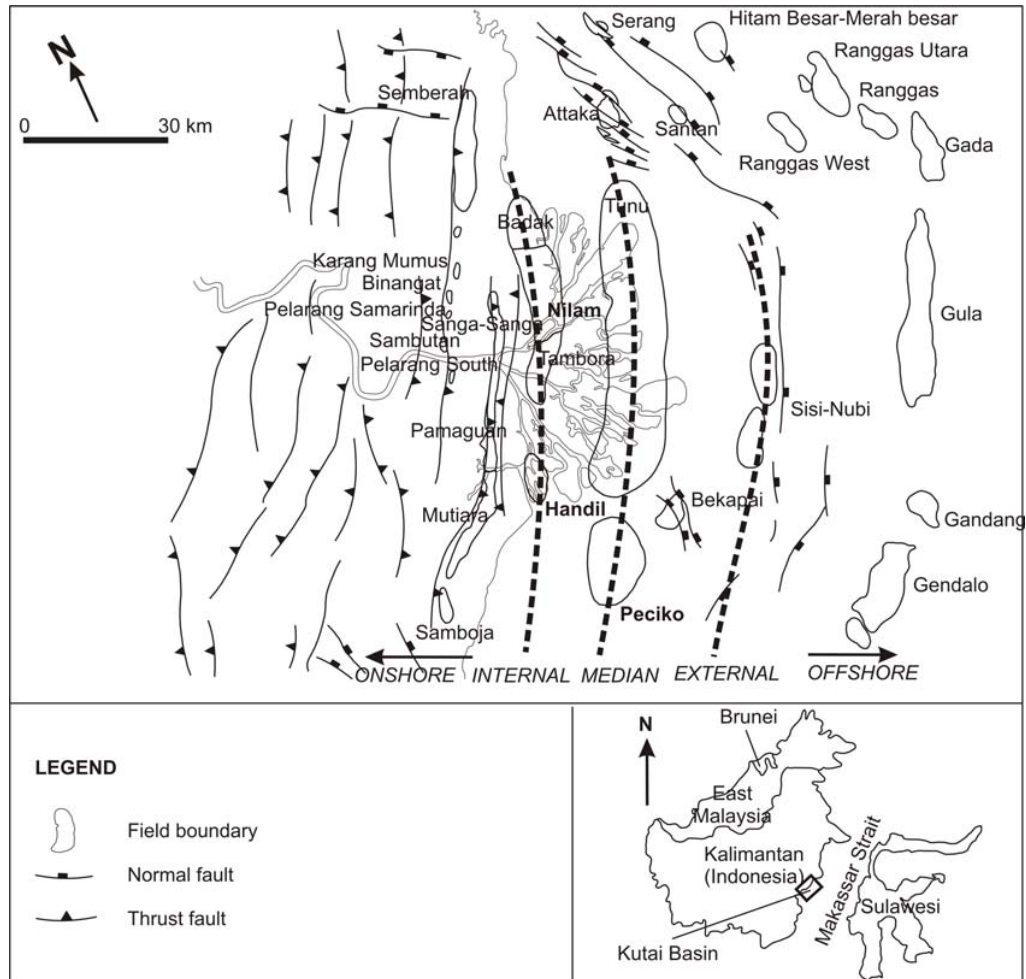


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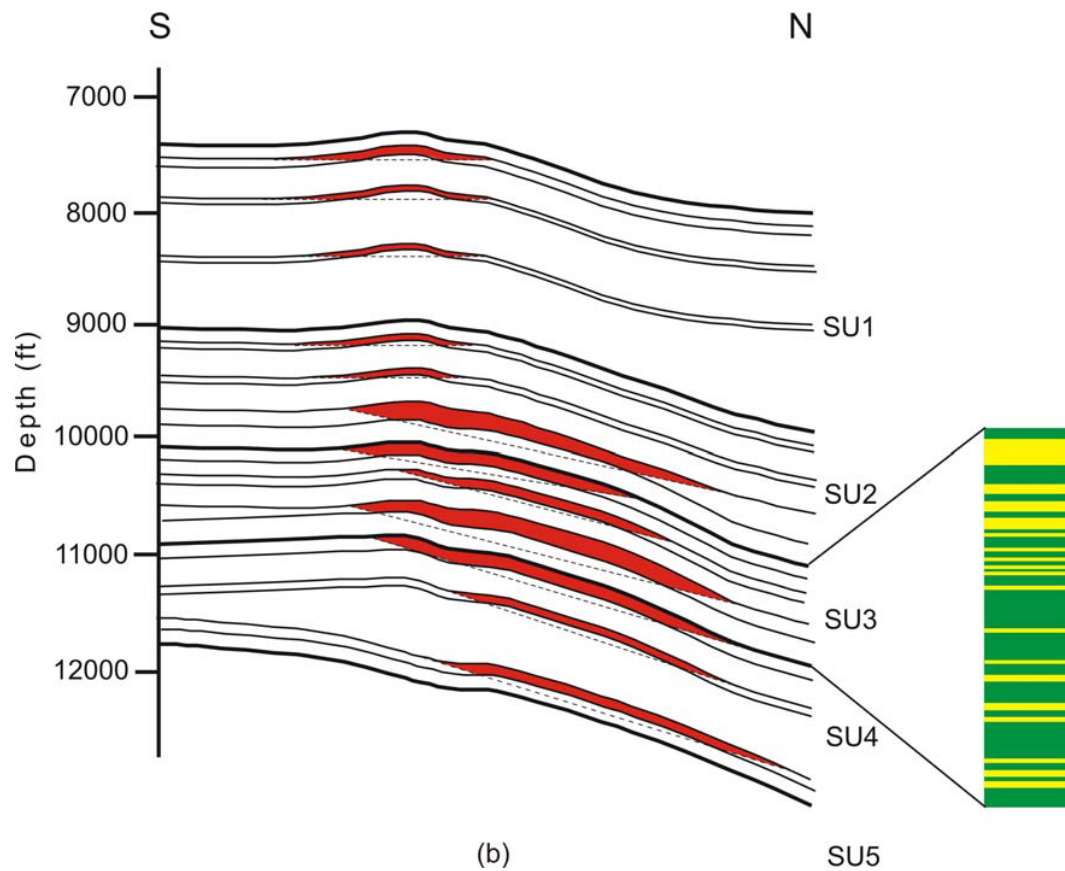
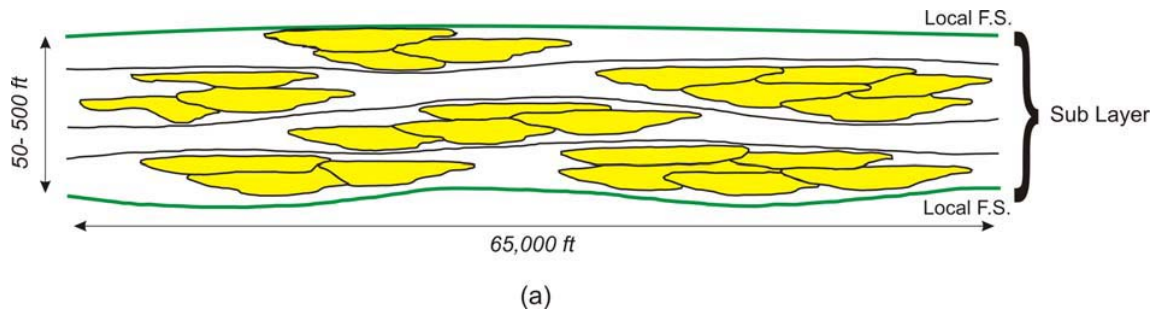


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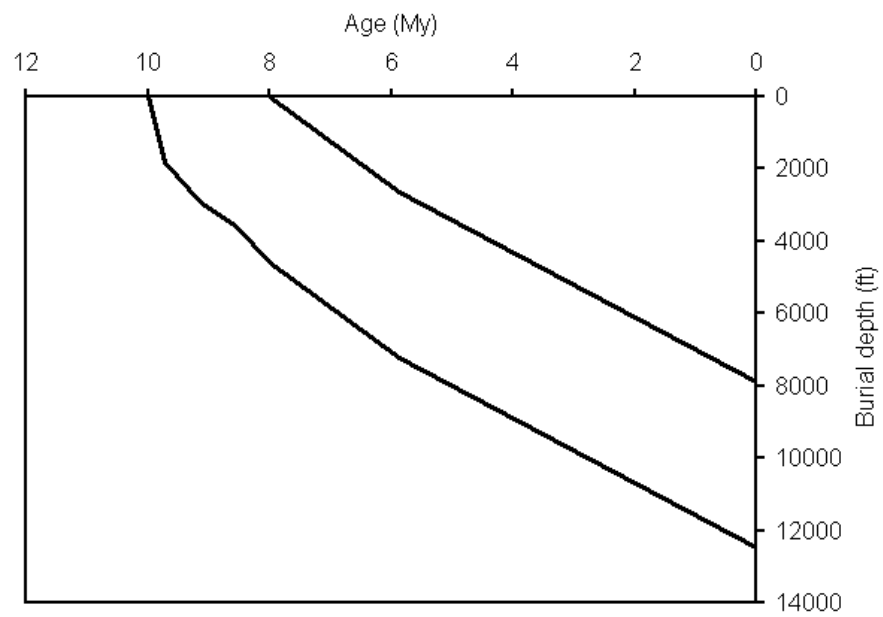
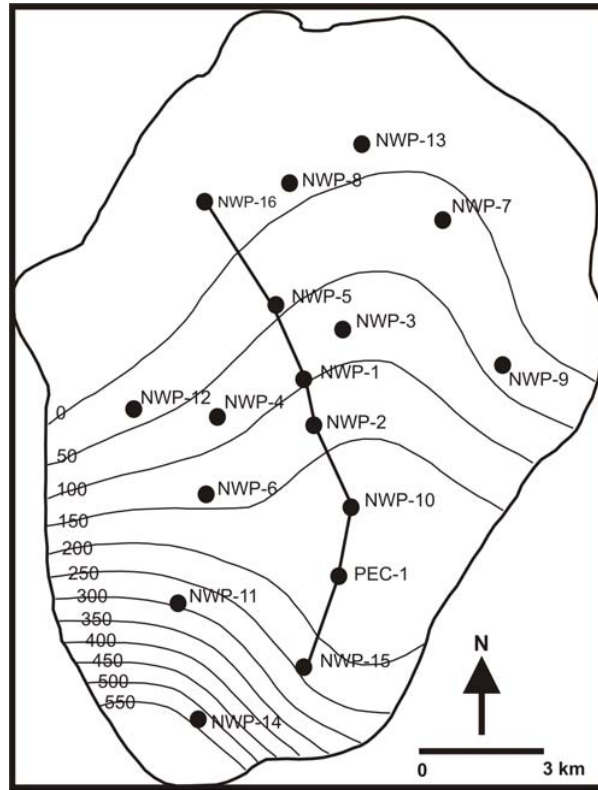
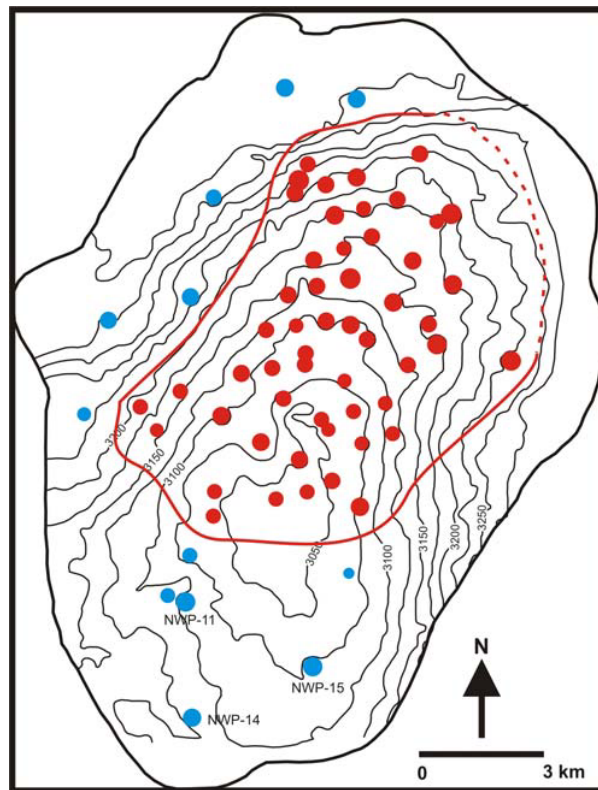


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(a)



(b)

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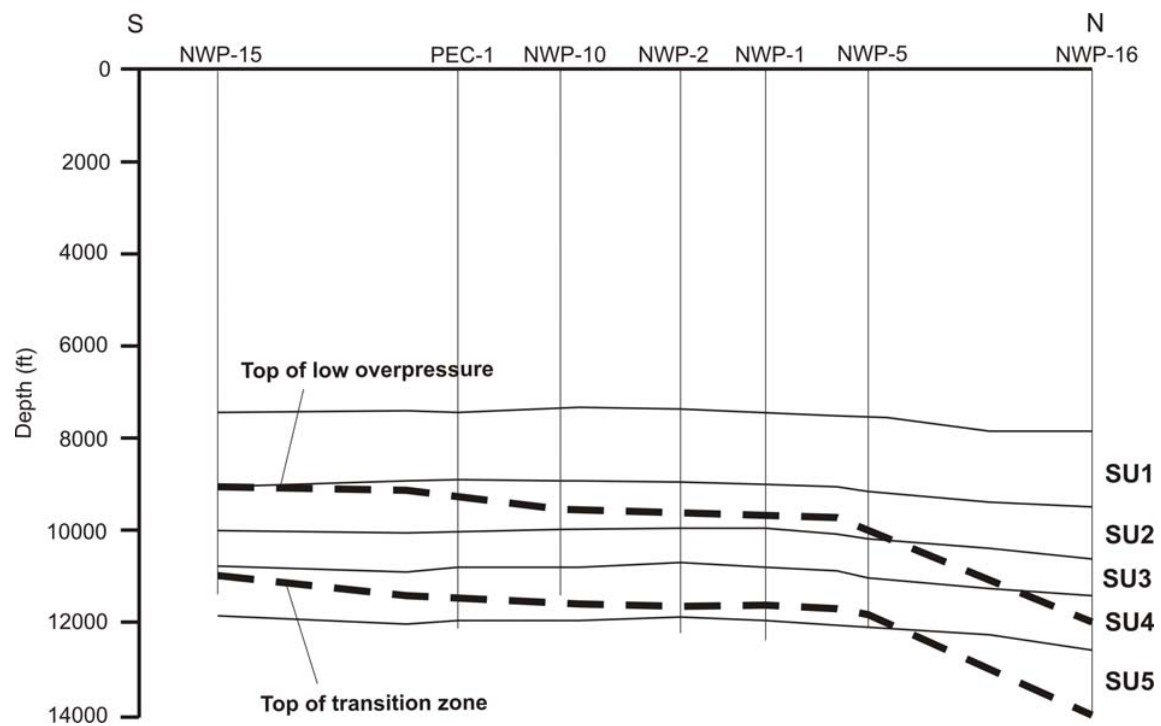


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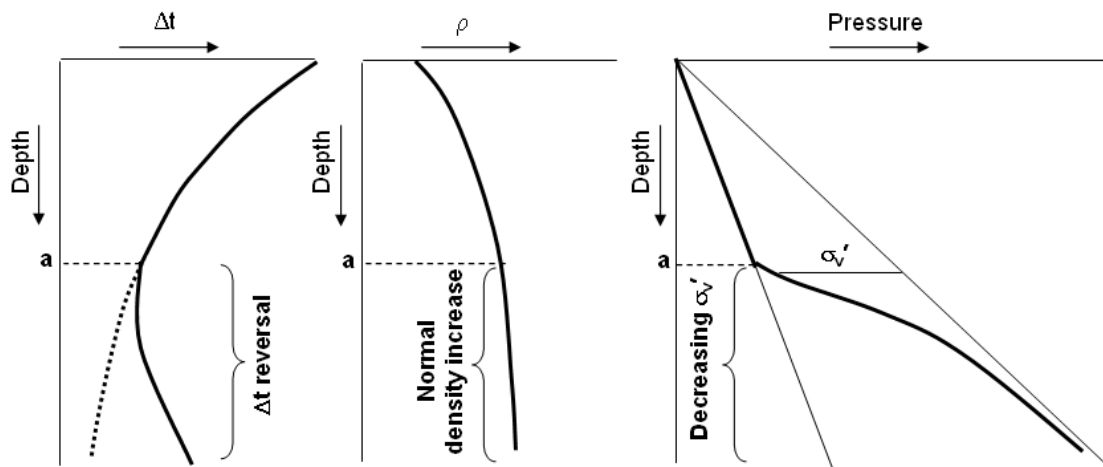


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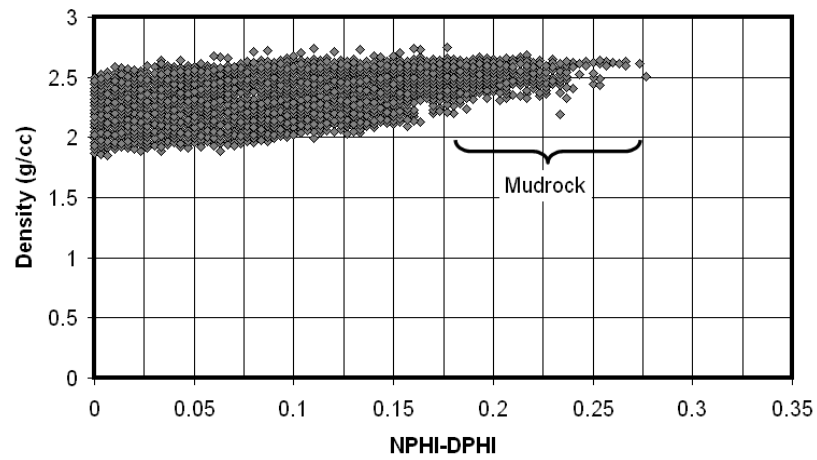


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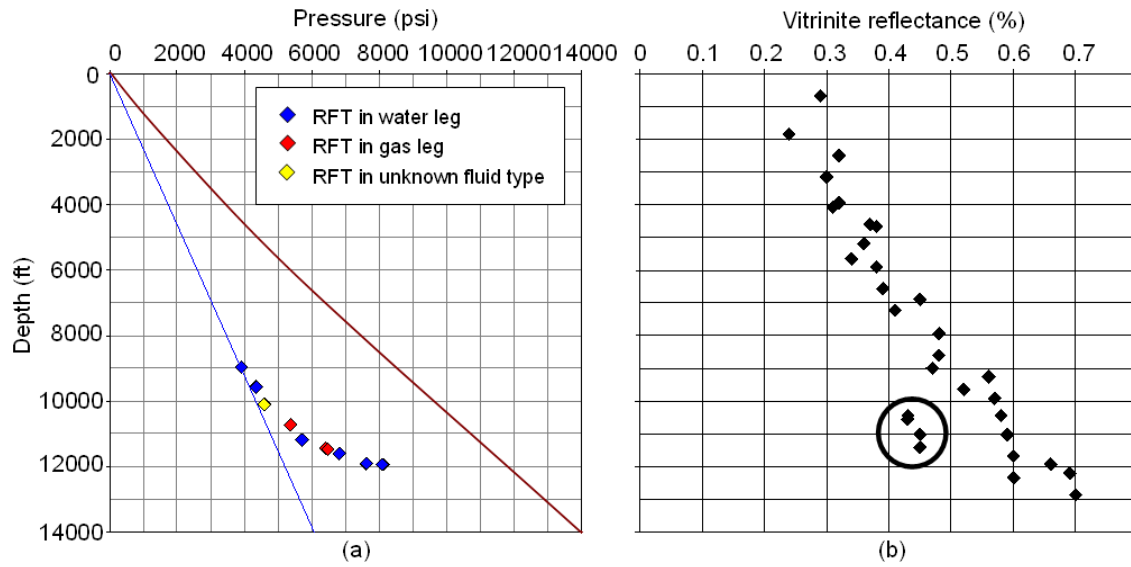


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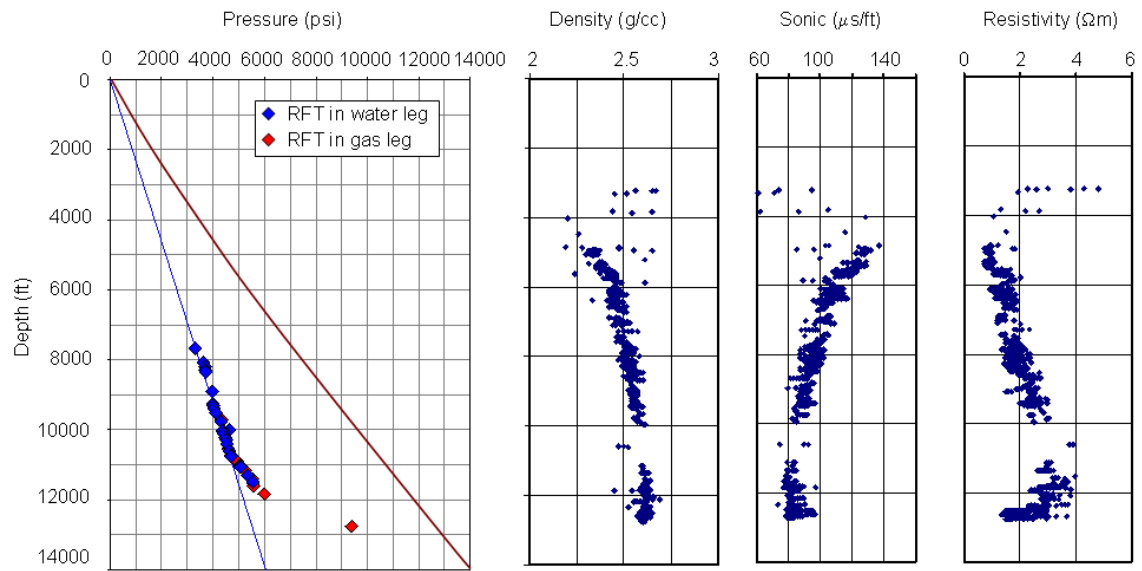


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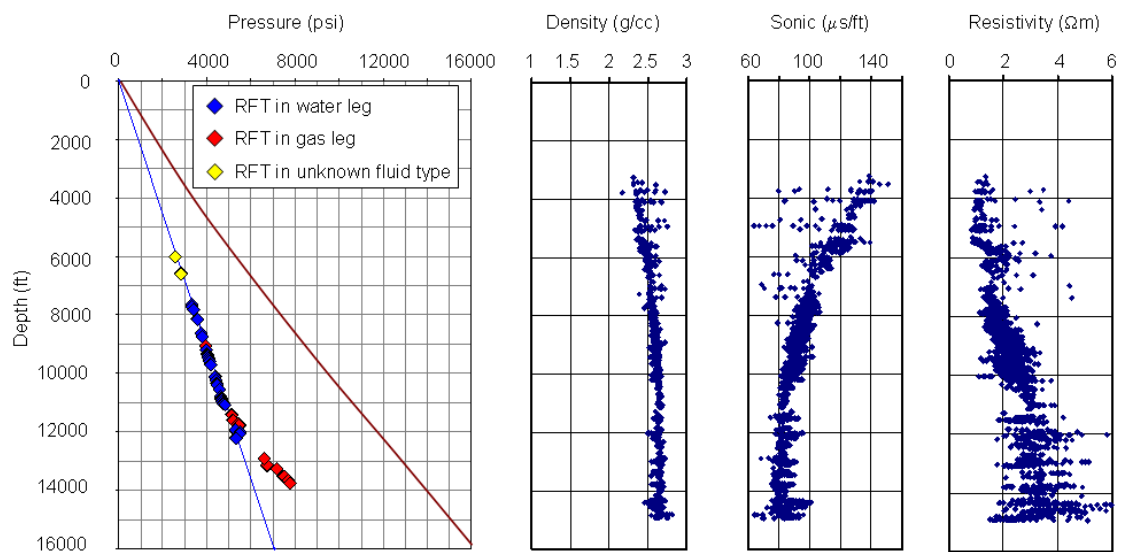


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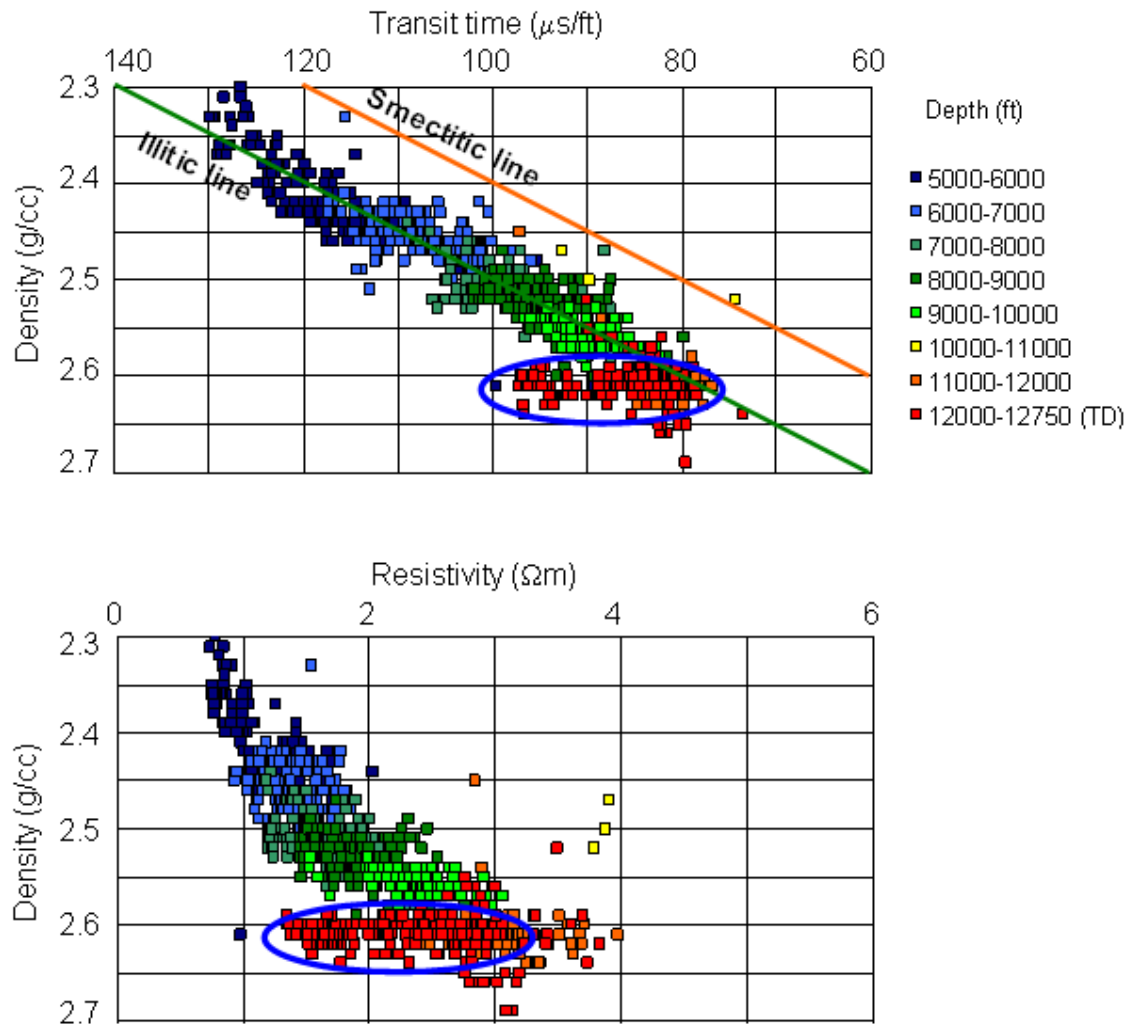


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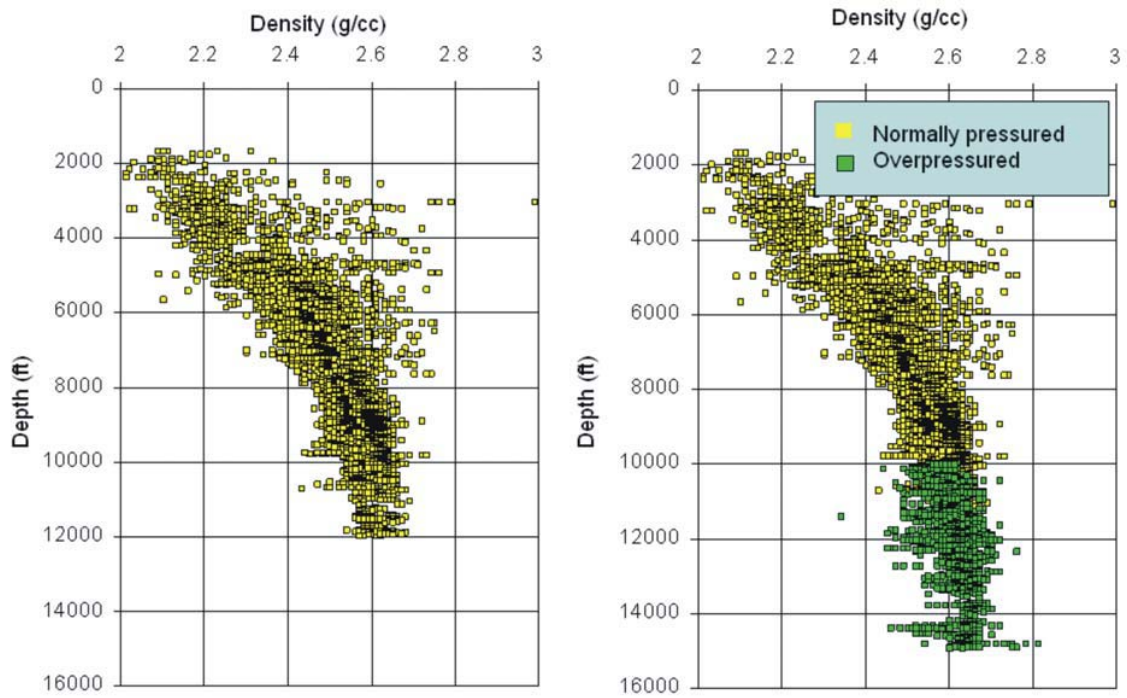


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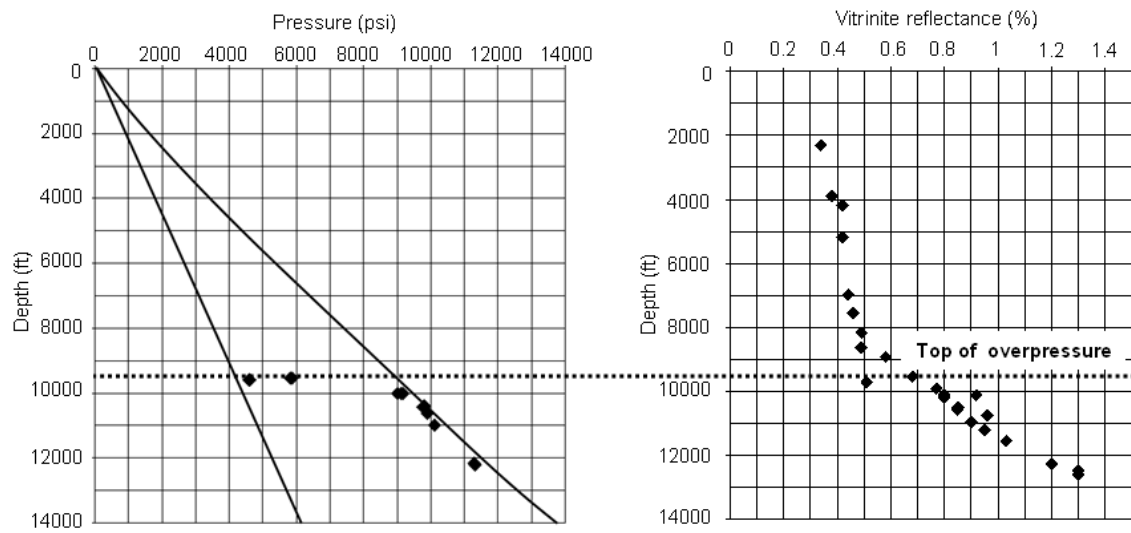


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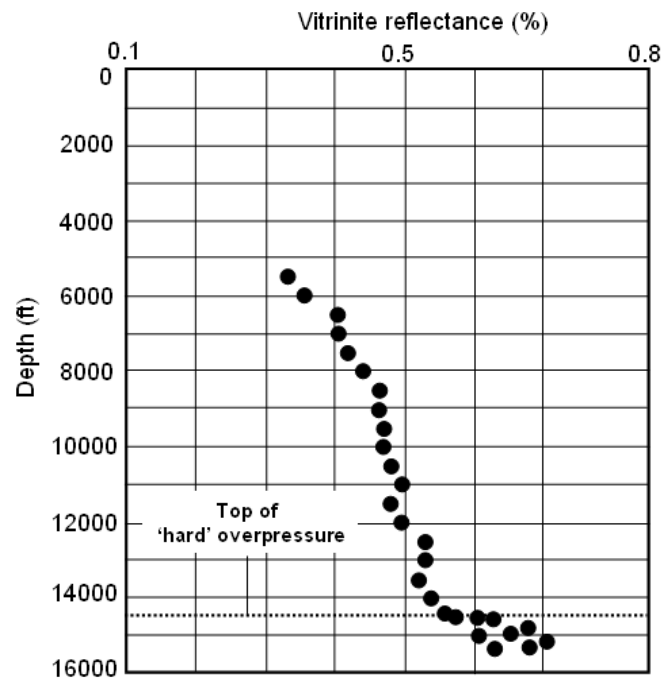


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